High Frequency Surface Wave Radar in the French Mediterranean Sea: an element of the Mediterranean Ocean Observing System for the Environment

Céline Gwenaëlle Quentin, Yves Barbin, Lucio Bellomo, Philippe Forget, Didier Mallarino, Julien Marmain, A. Molcard, Bruno Zakardjian

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Authors: C. Quentin (1), Y. Barbin (1), L. Bellomo (2,3), P. Forget (1), D. Mallarino (4), J. Marmain (1), A. Molcard (2,3), and B. Zakardjian (2,3)

(1) Aix Marseille Université, CNRS, Université de Toulon, IRD, MIO UM 110, 13288 Marseille, France. Celine.Quentin@mio.osupytheas.fr

(2) Aix Marseille Université, CNRS/INSU, IRD, MIO, UM 110, 13288 Marseille, France.

(3) Université de Toulon, CNRS/INSU, IRD, MIO, UM 110, 83957 La Garde, France.

(4) Aix Marseille Université, CNRS, IRD, OSU Pytheas UMS 3470, 13288, Marseille, France.

Abstract: A Mediterranean Ocean Observing System for the Environment (MOOSE) has been set up as an interactive, distributed, and integrated observatory system of the North West Mediterranean Sea in order to detect and identify long-term environmental anomalies. In this framework, the Mediterranean Institute of Oceanography (MIO) operates two couple of High Frequency Surface Wave Radars (HFSWR). HFSWRs provide synoptic observations of sea surface currents with high temporal (0.25-1 h) and spatial (1-3 km) resolution and long range (30-100 km). They can therefore be used to study the variability of the current as well as eddy dynamics. One site, based on the WERA (Helzel Messtechnik) technology and installed near Toulon, is operational and monitored in real-time since more than 3 years. It is composed of two WERA systems featuring respectively a non-linear receiving array and a full bistatic configuration, both working in Direction Finding mode. The second site, intended to extend further East the coverage of the Observatory, was set up in 2014 near Nice with two SeaSonde (Codar) systems. We present here an overview of the HFSWR network, the surface current mapping facility offered by the system, and recent observational results and applications.

Keywords: High Frequency Surface Wave Radar, Coastal Observing System, Northern Current, North Western Mediterranean Sea

1. INTRODUCTION

The Mediterranean Ocean Observing System for the Environment (MOOSE) focuses on documenting the long-term evolution of the North West (NW) Mediterranean Sea in the context of climate change and anthropogenic pressure. Furthermore, it targets building efficient indicators of the health of the basin. Finally, MOOSE will provide a large flux of real-time data to facilitate validation of operational oceanographic models.

The MOOSE concept is based on a multisite system of continental shelf and deep-sea fixed stations as well as on an autonomous mobile platform network devoted to the observation of the space-time variability of processes interacting between the coastal/open ocean and the ocean/atmosphere. It supplies and maintains long-term time series, thus allowing to evidence climatic trends. These data sets are included in the MISTRALS project and shall use the MyOcean data distribution infrastructure through Coriolis.

The predominant and most energetic circulation feature of the NW Mediterranean Sea is the Northern Current, a border current flowing cyclonically above the slope roughly over the 1000-2000 m isobaths. Its activity is highly variable. It is narrower, deeper and more intense during wintertime [Albérola *et al.*, 1995] with an intense mesoscale activity generating meanders, filaments, and eddies. Recent oceanographic studies in the Gulf of Lions (NW Mediterranean) have indeed shown the existence of vortex structures and instabilities in a wide range of scales. Namely, they have been well evidenced in the context of the ECCOLO campaign [Schaeffer *et al.*, 2011], where a certain number of *in situ* and remote sensors have been conjointly used, such as SST and water color satellite imagery, satellite-tracked drifting buoys and HF radar.

Today, High Frequency Surface Wave Radar (HFSWR) is indeed routinely used for the remote sensing of the ocean surface. Current measurements are obtained from the Doppler shift of the first-order Bragg-resonant echoes [Crombie, 1955]. The Mediterranean Institute of Oceanography (MIO) has proven its expertise in radar measurement of surface currents [Broche *et al.*, 1987, Molcard *et al.*, 2009] and has been assigned the task to deploy the HFSWR network for the MOOSE program.

2. DESCRIPTION OF THE SITES

The sites chosen for the HF radar network have been identified in order to cover the position of two instrumented lines (*Fig. 1*) with long time series of ocean parameters: ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch), and DYFAMED (DYnamics of Atmospheric Fluxes in the MEDiterranean sea). The main difficulties for deploying HFSWR lie in hardware and maintenance costs, frequency licenses, and site finding, especially when the coast is irregularly shaped, steep, or close to touristic and crowded regions.

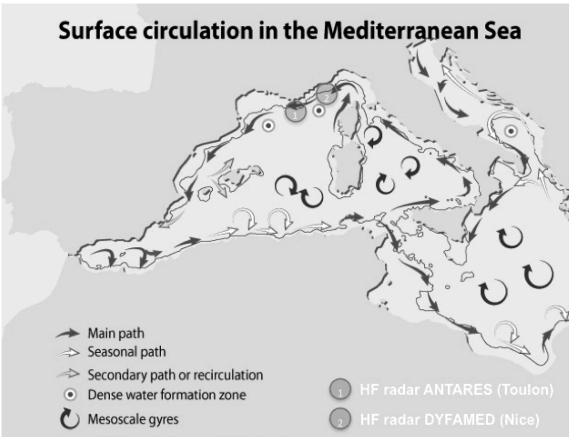

Fig. 1: Surface circulation scheme in the Western Basin of the Mediterranean Sea [Millot & Taupier-Letage, 2005] (cartographer GRID-Arendal) with the two site locations of the HFSWR measurements around the areas of interest: 1- Antares (near Toulon), 2- Dyfamed (near Nice).

3.1 First area of interest: ANTARES (Toulon)

The first target area off the coast of Toulon, related to the ANTARES instrumented line, is a key zone conditioning the behaviour of the North Current just upstream of the Gulf of Lions. It displays significant cross-shelf exchanges correlated to the strong northwesterlies present in the region (Mistral, Tramontane). This fully operational site is composed of two Wellen Radar (WERA [Gurgel *et al.*, 1998]) systems manufactured by Helzel Messtechnik GmbH providing real-time data. The first radar system has been installed at the Cap Sicié in 2010 and works in quasi-monostatic configuration with a non-linear, W-shaped, 8-antenna receiving array and a single emitting antenna. Such irregular configuration of the array was the only solution to cope with the insufficient space available.

This site has been complemented in May 2012 with a fully bistatic second system, a pioneering configuration for WERA at the time of the setup. The receiver, a regular linear 8-antenna array, is located at Cap Bénat while the transmitter, GPS-synchronized, is installed in the Porquerolles Island, 17 km away from the receiver, in order to circumvent the presence of several large islands. The bistatic configuration has required some dedicated and original hardware and software processing. It also allowed us to experimentally study the effects of bistatism on the HF Doppler spectra, namely evidencing good potential for the purpose of wave spectrum inversion [Grosdidier *et al.*, 2013].

Our systems are continuously working in the frequency band of 16.1 to 16.2 MHz allocated by the ITU (International Telecommunication Union) to the oceanographic radar operators. They sweep over a 50 kHz bandwidth, *i.e.* half of the allocated bandwidth, resulting in a 3 km range resolution. A 2 deg azimuthal resolution is achieved through a Direction Finding method based on Music [Lipa *et al.*, 2006, Molcard *et al.*, 2009]. The integration time can vary from 20 minutes to 1 hour. The radial velocities maps are transmitted every 20 minutes. Cartesian velocities are then reconstructed on a regular 2 x 2 km^2 grid (*Fig. 2*) and displayed in near real-time on a dedicated website:

http://hfradar.univ-tln.fr.

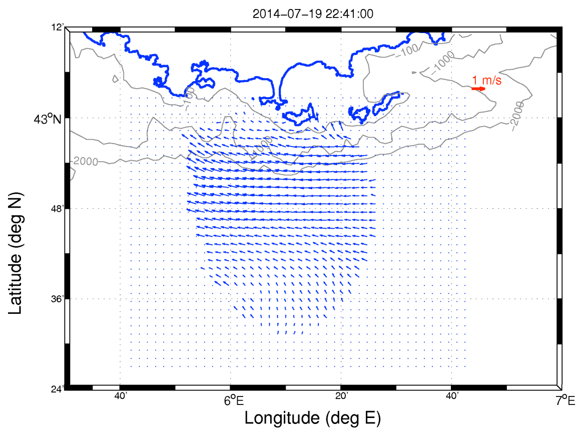

Fig. 2: ANTARES site. An example of Cartesian velocity map reconstructed on a grid 2x2 km^2 from the two radial velocity maps measured at the Cap Sicié and Cap Bénat sites using a Direction Finding method based on MUSIC.

3.2 Second area of interest: DYFAMED (Nice)

The installation of the second HFSWR site related to the DYFAMED buoy (*Fig. 3*) in the Ligurian Sea area,, extended the observation zone to the full coastal area between Toulon and Nice, allowing a much larger coverage of the Northern Current. The selected equipment is a pair of more compact HFSWR system, namely 2 SeaSondes from CODAR Ocean Sensors [Barrick, 1979]. The two locations are the lighthouse of Cap Ferrat in Saint-Jean Cap Ferrat (set up on October 2013) and the semaphore of Cap Dramont in Saint-Raphaël (set up on May 2014), resulting in a 50 km baseline. The latter was struck by a lightning in June 2014 and is currently off service.

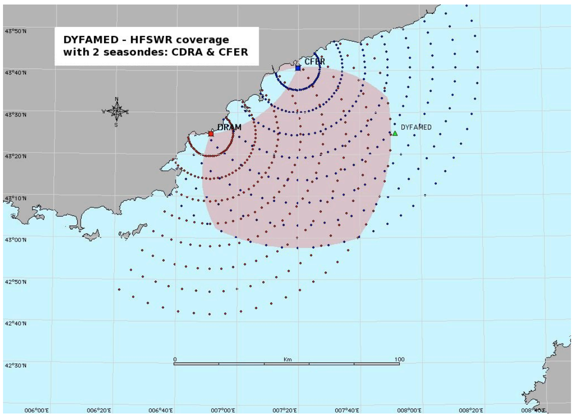

Fig. 3: DYFAMED site. Simulation of the coverage of each HFSWR station (Cap Dramont in red points, and Cap Ferrat in blue points) and coverage of the Cartesian velocity map (pink area).

Our pair of SeaSondes works in the 13.5 MHz frequency band allocated by the ITU with a 50 kHz bandwidth. The parameters are similar to those of the WERA systems, except for the azimuthal resolution set at 5 deg.

The ever-increasing deployment of HFSWRs has led the international community to build a frequency sharing plan. Although our radars follow the ITU's recommendations and operate over the frequency bands specified for oceanographic purposes, strong Radio Frequency Interference (RFI) is often present, due to official and non-official radio services. The result is a radical reduction in coverage and the presence of outliers in the velocity maps.

3. DATA FLOW AND QUALITY CONTROLS

The first product of the measurement made by a HFSWR is the radial velocity. Total vector is a combination of less two HFSWR measurements. The quality insurance of the total vector map is depending of all the steps of the processing chain, so the quality control must be hierarchized as following with in first the control of the instrument and in second the control of the measurement on each component related to each site.

Level 0 – Availability of the instrument

Our first indicator is related to the first level of the data acquisition chain and determines if the data is available or not. A first diagnostic is done on the HFSWR system: controlling if emitter and receiver are properly functioning (and well synchronized if necessary using GPS timing service), and if the contamination by radio interference is not prejudicial to the measurement. Theses diagnostics alert the operator of troubleshooting on the hardware system.

The coverage of the radial velocity measurement is then analysed. If the coverage is not sufficient the radial file is rejected. The number of radial files per ten days is a good indicator (Fig. 4) on the availability of the data.

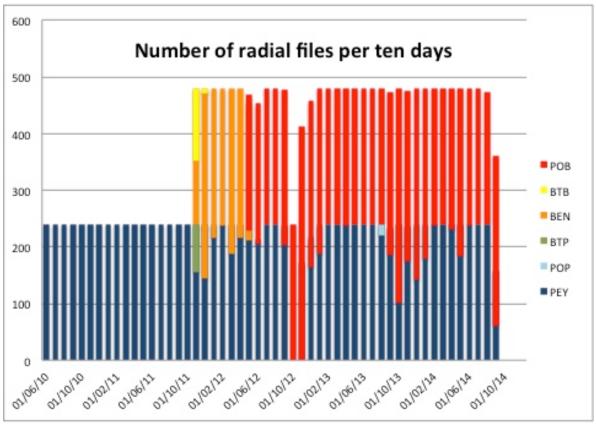

Fig. 4: ANTARES: availability of the data given by the number of radial files per ten days on each couple of receiver/transmitter according to the different mono and bi-static configurations. The main ones are in blue PEY- collocated receiver and transmitter, and POB- Porquerolles transmitter/Cap Bénat receiver.

Level 1 – Control of the instrument

Best practices for the operation and maintenance of HFSWRs prescribe regular measurement of directional antenna pattern of the receiver as a necessary component of the quality assurance and quality control [Cook *et al.*, 2008]. An idealised antenna pattern can be used for a first guess, but it doesn't take into account the environment of the site. We perform at least every year an Antenna Pattern Measurement (APM) on each HFSWR site. The comparison between different measurements ensured the stability of the antenna system and characterised the performance of the system.

Level 2 – Measurement performance

On ANTARES area, different campaigns (TOSCA, SUBCORAD and BOMBYX) allow us to validate the HFSWR radial velocities measurements by comparison with *in situ* measurements as lagrangian drifters and ADCP (tracked and moored). The comparisons give good agreement in the limits of the intrinsic radar accuracy, in the order of 5 $cm.s^{-1}$ [Fraunié *et al.*, 2014].

4. APPLICATIONS

The applications of our HFSWR measurements have spanned the fields of ocean circulation to operational oceanography to methodological development.

In the first step of the ANTARES implementation (2010-2011), when only one radar site was operational (Cap Sicié), [Marmain *et al.*, 2011] developed and successfully tested the Vortex Identification Method (VIM) to reveal the presence of eddy-like structures through radial current velocity maps. During the PHYOCE experiment (March, 31 – April, 3 2011) the variability of the current flow was deduced from the radial velocity field and was used in complement to *in-situ* measurements to confirm the existence of a mesoscale meander. This was also visible in the numerical model of circulation GLAZUR-64 developed at MIO [Guihou *et al.*, 2013].

Full vector current maps are available since late 2011 in the ANTARES site. Two experiments were performed in the framework of the TOSCA (Tracking Oil Spills & Coastal Awareness network) project, a EU-funded MedProgram, gathering a comprehensive data set of surface drifter trajectories and *in-situ* measurements (including gliders) in the HFSWR area. These data have been combined into a web-based decision tool designed for authorities in charge of maritime crisis such as Search-and-Rescue and oil spills. Surface drifter trajectories have also served to validate the HFSWR velocities, and to develop a new tool for blending both kinds of measurements [Berta *et al.*, 2014]. Finally, hydrological data have complemented HFSWR current velocity maps in order to study the Northern Current variability under wind forcing [Bellomo *et al.*, 2013].

The potential of this real-time observation lies also in the possibility of assimilating the surface current velocities in numerical oceanic models. As an example, [Marmain *et al.*, 2014] successfully used the HFSWR data to correct hydrographic boundary conditions as well as the wind forcing.

Finally, two projects are currently focusing on the physical understanding of the HFSWR current measurement. Namely, SUBCORAD is investigating the impact of sub-grid variability, whereas within STRING surface drifters designed to sense the vertical shear of the current as the HFSWR does have been built and experimentally tested.

5. CONCLUSIONS

An HFSWR network has being deployed by the MIO along the Mediterranean coast of France, including both WERA and SeaSonde systems. For the former ones, some innovative technical solutions have allowed to solve limitations due to the geographical configuration of the sites, including the successful use of a non-linear array of antennas and the exploitation of a full bistatic configuration. Furthermore, a Direction Finding algorithm based on MUSIC has for the first time been used with a WERA system, and adapted to the bistatic case.

Antenna Pattern Measurements are routinely performed to take into account the specificity of the environment where the antennas are placed as well as their ageing. Validation experiments have been performed, demonstrating the accuracy of the HFSWR-derived surface current velocity maps as well as their importance for operational oceanography as well as circulation studies.

With a dataset of more than four years of radial velocity maps and two years of total ones for the first site (ANTARES), this work is the start of a long-term observational effort with HFSWR aimed at providing continuous surface current data in the context of the MOOSE program.

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